

# Tri- and tetranuclear molybdenum and tungsten chalcogenide clusters: On the way to new materials and catalysts

Kazan Federal University, 420008, Kremlevskaya 18, Kazan, Russia

---

## Abstract

© 2018 Uspekhi Khimii, Russian Academy of Sciences and Turpion Ltd. Data on the electronic structure and redox, magnetic, luminescent, nonlinear optical and catalytic properties of tri- and tetranuclear molybdenum and tungsten chalcogenide clusters are analyzed and integrated. The prospects for the applications of this family of clusters for the design of new materials for molecular electronics, nonlinear optics and catalysis are considered. The bibliography includes 202 references.

<http://dx.doi.org/10.1070/RCR4800>

---

## References

- [1] A.A. Opalovskii, V.E. Fedorov, K.A. Khaldoyanidi. Dokl. Akad. Nauk SSSR, 182, 1095 (1968)
- [2] T. Shibahara. Coord. Chem. Rev., 123, 73 (1993)
- [3] G. Sakane, T. Shibahara, in Transition Metal Sulfur Chemistry. ACS Simp. Ser. Vol. 653. (Washington, DC: American Chemistry Society, 1996). p. 225
- [4] T. Saito. Adv. Inorg. Chem., 44, 45 (1996)
- [5] R. Llusar, C. Vicent. Inorg. Chem. Focus III, 105 (2006)
- [6] V.E. Fedorov, Yu.V. Mironov, N.G. Naumov, M.N. Sokolov, V.P. Fedin. Russ. Chem. Rev., 76, 529 (2007)
- [7] R. Hernandez-Molina, M.N. Sokolov, P.A. Abramov, in Incomplete and Complete Cuboidal Clusters of Molybdenum Chemistry. (Ed. A. Holders). (New York: Nova Science, 2013). p. 105
- [8] A. Müller, R. Jostes, F.A. Cotton. Angew. Chem., Int. Ed. Engl., 474, 875 (1980)
- [9] K. Hegetschweiler, T. Keller, M. Baeumle, G. Rihs, W. Schneider. Inorg. Chem., 30, 4342 (1991)
- [10] A. Müller, R. Jostes, W. Jaegermann, R. Bhattacharyya. Inorg. Chim. Acta, 41, 259 (1980)
- [11] A. Alberola, R. Llusar, S. Triguero, C. Vicent, M.N. Sokolov, C. Gómez-García. J. Mater. Chem., 17, 3440 (2007)
- [12] R. Llusar, S. Triguero, C. Vicent, M.N. Sokolov, B. Domercq, M. Fourmigué. Inorg. Chem., 44, 8937 (2005)
- [13] A.L. Gushchin, R. Llusar, C. Vicent, P.A. Abramov, C.J. Gómez-García. Eur. J. Inorg. Chem., 2615 (2013)
- [14] D. Recatala, R. Llusar, A.L. Gushchin, E.A. Kozlova, Yu.A. Laricheva, P.A. Abramov, M.N. Sokolov, R. Gómez, T. Lana-Villarreal. Chem Sus Chem, 8, 148 (2015)
- [15] J.M. Garriga, R. Llusar, S. Uriel, C. Vicent, A.J. Usher, N.T. Lucas, M.G. Humphrey, M. Samoc. Dalton Trans., 4546 (2003)
- [16] M.J. Mayor-López, J. Weber, K. Hegetschweiler, M.D. Meienberger, F. Joho, S. Leoni, R. Nesper, G.J. Reiss, W. Frank, B.A. Kolesov, V.P. Fedin, V.E. Fedorov. Inorg. Chem., 37, 2633 (1998)
- [17] A.L. Gushchin, M.N. Sokolov, E.V. Peresyphkina, A.V. Virovets, S.G. Kozlova, N.F. Zakharchuk, V.P. Fedin. Eur. J. Inorg. Chem., 3964 (2008)
- [18] R. Llusar, S. Triguero, V. Polo, C. Vicent, C.J. Gómez-García, O. Jeannin, M. Fourmigué. Inorg. Chem., 47, 9400 (2008)

- [19] I.J. McLean, R. Hernandez-Molina, M.N. Sokolov, M.S. Seo, A.V. Virovets, M.R.J. Elsegood, W. Clegg, A.G. Sykes. *J. Chem. Soc, Dalton Trans.*, 2557 (1998)
- [20] R. Llusar, S. Uriel, C. Vicent, J.M. Clemente-Juan, E. Coronado, C.J. Gómez-García, B. Braida, E. Canadell. *J. Am. Chem. Soc.*, 126, 12076 (2004)
- [21] R. Llusar, C. Vicent. *Coord. Chem. Rev.*, 254, 1534 (2010)
- [22] A. Müller, R. Jostes, W. Eltzner, C.-S. Nie, E. Diemann, H. Bogge, M. Zimmermann, M. Dartmann, U. Reinsch-Vogell, S. Che, S.J. Cyvin, B.N. Cyvin. *Inorg. Chem.*, 24, 2872 (1985)
- [23] F.A. Cotton, X. Feng. *Inorg. Chem.*, 30, 3666 (1991)
- [24] R.E. Cramer, K. Yamada, H. Kawaguchi, K. Tatsumi. *Inorg. Chem.*, 35, 1743 (1996)
- [25] J. Mizutani, H. Imoto, T. Saito. *J. Clust. Sci.*, 8, 155 (1997)
- [26] P.A. Petrov, D.Y. Naumov, R. Llusar, C.J. Gómez-García, V. Polo, S.N. Konchenko. *Dalton Trans.*, 41, 14031 (2012)
- [27] T. Weber, J.C. Muijsers, J.W. Niemantsverdriet. *J. Phys. Chem.*, 99, 9194 (1995)
- [28] J.C. Muijsers, T. Weber, R.M. van Hardeveld, H.W. Zandbergen, J.W. Niemantsverdriet. *J. Catal.*, 157, 698 (1995)
- [29] H. Akashi, T. Shibahara. *Inorg. Chim. Acta*, 300, 572 (2000)
- [30] J. Andres, M. Feliz, J. Fraxedas, V. Hernandez, J.T. Lopez-Navarrete, R. Llusar, G. Sauthier, F.R. Sensato, B. Silvi, C. Bo, J.M. Campanera. *Inorg. Chem.*, 46, 2159 (2007)
- [31] M. Feliz, R. Llusar, J. Andrés, S. Berski, B. Silvi. *New J. Chem.*, 26, 844 (2002)
- [32] J. Andrés, S. Berski, M. Feliz, R. Llusar, F. Sensato, B. Silvi. *C. R. Chim.*, 8, 1400 (2005)
- [33] J. Li, C.-W. Liu, J.-X. Lu. *Polyhedron*, 13, 1841 (1994)
- [34] W.-D. Cheng, G.-C. Guo, J.-S. Huang, L.-J. Lu. *Polyhedron*, 14, 3649 (1995)
- [35] Z. Chen, J. Lu, C. Liu, Z. Qianer. *Polyhedron*, 10, 2799 (1991)
- [36] C. Wendan, Z. Qianer, H. Jinshun, L. Jiayi. *Polyhedron*, 9, 1625 (1990)
- [37] C. Wendan, Z. Qianer, H. Jinshun, J. Lu. *Polyhedron*, 8, 2785 (1989)
- [38] J. Li, C.W. Liu, J.X. Lu. *J. Clust. Sci.*, 5, 505 (1994)
- [39] F. Estevan, M. Feliz, R. Llusar, J.A. Mata, S. Uriel. *Polyhedron*, 20, 527 (2001)
- [40] M. Feliz, R. Llusar, S. Uriel, C. Vicent, M.G. Humphrey, N.T. Lucas, M. Samoc, B. Luther-Davies. *Inorg. Chim. Acta*, 349, 69 (2003)
- [41] R. Hernandez-Molina, M. Sokolov, W. Clegg, P. Esparza, A. Mederos. *Inorg. Chim. Acta*, 331, 52 (2002)
- [42] K. Herbst, P. Zanello, M. Corsini, N. D'Amelio, L. Dahlenburg, M. Brorson. *Inorg. Chem.*, 42, 974 (2003)
- [43] N. Avarvari, K. Kiracki, R. Llusar, V. Polo, I. Sorribes, C. Vicent. *Inorg. Chem.*, 49, 1894 (2010)
- [44] R. Llusar, S. Uriel. *Eur. J. Inorg. Chem.*, 1271 (2003)
- [45] E. Pedrajas, I. Sorribes, A.L. Gushchin, Yu.A. Laricheva, K. Junge, M. Beller, R. Llusar. *Chem Cat Chem*, 9, 1128 (2017)
- [46] J.A. Pino-Chamorro, Yu.A. Laricheva, E. Guillamón, M.J. Fernandez-Trujillo, E. Bustelo, A.L. Gushchin, N.Y. Shmelev, P.A. Abramov, M.N. Sokolov, R. Llusar, M.G. Basallote, A.G. Algarra. *New J. Chem.*, 40, 7872 (2016)
- [47] A.L. Gushchin, Yu.A. Laricheva, D.A. Piryazev, M.N. Sokolov. *Russ. J. Coord. Chem.*, 40, 5 (2014)
- [48] A.L. Gushchin, Yu.A. Laricheva, P.A. Abramov, A.V. Virovets, C. Vicent, M.N. Sokolov, R. Llusar. *Eur. J. Inorg. Chem.*, 4093 (2014)
- [49] P.A. Petrov, A.V. Virovets, A.S. Bogomyakov, R. Llusar, C.J. Gomez-Garcia, V. Polo, S.N. Konchenko. *Chem. Commun.*, 48, 2713 (2012)
- [50] M.G. Basallote, M. Feliz, M.J. Fernandez-Trujillo, R. Llusar, V.S. Safont, S. Uriel. *Chem.-Eur. J.*, 10, 1463 (2004)
- [51] P.A. Petrov, A.V. Virovets, A. Alberola, R. Llusar, S.N. Konchenko. *Dalton Trans.*, 51, 8875 (2010)
- [52] T. Saito, N. Tamamoto, T. Yamagata, H. Imoto. *J. Am. Chem. Soc.*, 110, 1646 (1988)
- [53] K. Tsuge, H. Imoto, T. Saito. *Inorg. Chem.*, 34, 3404 (1995)
- [54] P.A. Petrov, M.R. Ryzhikov, A.V. Virovets, S.N. Konchenko, C.J. Gómez-García, R. Llusar. *Polyhedron*, 81, 6 (2014)
- [55] C.S. Bahn, A. Tan, S. Harris. *Inorg. Chem.*, 37, 2770 (1998)
- [56] T. Shibahara, G. Sakane, Y. Naruse, K. Taya, H. Akashi, A. Ichimura, H. Adachi. *Bull. Chem. Soc. Jpn.*, 68, 2769 (1995)
- [57] K. Hegetschweiler, M. Wöerle, M.D. Meienberger, R. Nesper, H.W. Schmalle, R.D. Hancock. *Inorg. Chim. Acta*, 250, 35 (1996)
- [58] R. Miyamoto, S. Kawata, M. Iwaizumi, H. Akashi, T. Shibahara. *Inorg. Chem.*, 36, 542 (1997)

- [59] T. Yamauchi, H. Takagi, T. Shibahara, H. Akashi. *Inorg. Chem.*, 45, 5429 (2006)
- [60] M. Feliz, J.M. Garriga, R. Llusar, S. Uriel, M.G. Humphrey, N.T. Lucas, M. Samoc, B. Luther-Davies. *Inorg. Chem.*, 40, 6132 (2001)
- [61] R. Llusar, S. Uriel, C. Vicent. *J. Chem. Soc, Dalton Trans.*, 2813 (2001)
- [62] R. Llusar, I. Sorribes, C. Vicent. *Inorg. Chem.*, 48, 4837 (2009)
- [63] J.A.A. Pino-Chamorro, Yu.A. Laricheva, E. Guillamón, M.J. Fernandez-Trujillo, A.G. Algarra, A.L. Gushchin, P.A. Abramov, E. Bustelo, R. Llusar, M.N. Sokolov, M.G. Basallote. *Inorg. Chem.*, 55, 9912 (2016)
- [64] M. Feliz, R. Llusar, S. Uriel, C. Vicent, E. Coronado, C.I. Gómez-García. *Chem.-Eur. J.*, 10, 4308 (2004)
- [65] I. Sorribes, F. Lloret, J.C. Waerenborgh, V. Polo, R. Llusar, C. Vicent. *Inorg. Chem.*, 51, 10512 (2012)
- [66] A.L. Gushchin, K.A. Kovalenko, M.N. Sokolov, D.Y. Naumov, N.F. Zakharchuk, C. Vicent, V.P. Fedin. *Russ. Chem. Bull.*, 56, 1701 (2007)
- [67] A. Alberola, R. Llusar, C. Vicent, J. Andrés, V. Polo, C.J. Gómez-García. *Inorg. Chem.*, 47, 3661 (2008)
- [68] H. Akashi, N. Uryu, T. Shibahara. *Inorg. Chim. Acta*, 261, 53 (1997)
- [69] P.W. Dimmock, D.P.E. Dickson, A.G. Sykes. *Inorg. Chem.*, 29, 5120 (1990)
- [70] N.A. Kryuchkova, M.M. Syrovashin, A.L. Gushchin, E.V. Korotaev, A.V. Kalinkin, Yu.A. Laricheva, M.N. Sokolov. *Spectrochim. Acta, Part A*, 190, 347 (2018)
- [71] S. Krackl, A. Alberola, R. Llusar, G. Meyer, C. Vicent. *Inorg. Chim. Acta*, 363, 4197 (2010)
- [72] P.A. Petrov, D.Y. Naumov, T.S. Sukhikh, S.N. Konchenko, C.J. Gómez-García, R. Llusar. *New J. Chem.*, 41, 7849 (2017)
- [73] D. Recatala, R. Llusar, F. Galindo, K.A. Brylev, A.L. Gushchin. *Eur. J. Inorg. Chem.*, 1877 (2015)
- [74] D. Recatala, A.L. Gushchin, R. Llusar, F. Galindo, K.A. Brylev, M.R. Ryzhikov, N. Kitamura. *Dalton Trans.*, 42, 12947 (2013)
- [75] *Optoelectronic Properties of Inorganic Compounds*. (Eds D.M. Roundhill, J.P. Fackler). (Boston: Springer, 1999)
- [76] W. Zhang, W.Y. Jiao, G. Shi, Y.L. Song, Y.X. Wang, D.J. Liu, Q. Chang, C. Zhang, X.Q. Xin. *Opt. Mater. (Amsterdam)*, 31, 218 (2008)
- [77] Q.F. Zhang, Y.N. Xiong, T.S. Lai, W. Ji, X.Q. Xin. *J. Phys. Chem. B*, 104, 3446 (2000)
- [78] S. Shi, W. Ji, S.H. Tang, J.P. Lang, X.Q. Xin. *J. Am. Chem. Soc*, 116, 3615 (1994)
- [79] S. Shi, Z.R. Chen, H.W. Hou, X.Q. Xin, K.B. Yu. *Chem. Mater.*, 7, 1519 (1995)
- [80] G. Sakane, T. Shibahara, H.W. Hou, X.Q. Xin, S. Shi. *Inorg. Chem.*, 34, 4785 (1995)
- [81] R. Philip, P. Chantharasupawong, H.F. Qian, R.C. Jin, J. Thomas. *Nano Lett.*, 12, 4661 (2012)
- [82] S.A. Khan, D. Senapati, T. Senapati, P. Bonifassi, Z. Fan, A.K. Singh, A. Neeley, G. Hill, P.C. Ray. *Chem. Phys. Lett.*, 512, 92 (2011)
- [83] W. Ji, S. Shi, H.J. Du, P. Ge, S.H. Tang, X.Q. Xin. *J. Phys. Chem.*, 99, 17297 (1995)
- [84] P. Ge, S.H. Tang, W. Ji, S. Shi, H.W. Hou, D.L. Long, X.Q. Xin, S.F. Lu, Q.J. Wu. *J. Phys. Chem. B*, 101, 27 (1997)
- [85] S. Shi, H.W. Hou, X.Q. Xin. *J. Phys. Chem.*, 99, 4050 (1995)
- [86] J. Dai, C.Q. Bian, X. Wang, Q.F. Xu, M.Y. Zhou, M. Munakata, M. Maekawa, M.H. Tong, Z.R. Sun, H.P. Zeng. *J. Am. Chem. Soc*, 122, 11007 (2000)
- [87] G. Chatzikyriakos, I. Papagiannouli, S. Couris, G.C. Anyfantis, G.C. Papavassiliou. *Chem. Phys. Lett.*, 513, 229 (2011)
- [88] D. Recatala, R. Llusar, A. Barlow, G.M. Wang, M. Samoc, M.G. Humphrey, A.L. Gushchin. *Dalton Trans.*, 44, 13163 (2015)
- [89] A.V. Rogachev, A.L. Gushchin, P.A. Abramov, E.A. Kozlova, C. Vicent, D. Pirayezev, A. Barlow, M. Samoc, M.G. Humphrey, R. Llusar, V.P. Fedin, M.N. Sokolov. *Eur. J. Inorg. Chem.*, (17), 2865 (2015)
- [90] A. Nova, R. Mas-Ballesté, A. Lledós. *Organometallics*, 31, 1245 (2011)
- [91] E. Clot, O. Eisenstein, N. Jasim, S.A. Macgregor, J.E. McGrady, R.N. Perutz. *Ace. Chem. Res.*, 44, 333 (2011)
- [92] X. Ribas. *C-H and C-X Bond Functionalization: Transition Metal Mediation*. (Ed. J.J. Spivey). (Cambridge: The Royal Society of Chemistry, 2013)
- [93] B.M. Kraft, R.J. Lachicotte, W.D. Jones. *J. Am. Chem. Soc*, 122, 8559 (2000)
- [94] M.F. Kuhnelt, D. Lentz. *Angew. Chem., Int. Ed*, 49, 2933 (2010)
- [95] S. Yow, S.J. Gates, A.J.P. White, M.R. Crimmin. *Angew. Chem., Int. Ed*, 51, 12559 (2012)
- [96] M.F. Kuehnelt, P. Holstein, M. Kliche, J. Kruger, S. Matthies, D. Nitsch, J. Schutt, M. Sparenberg, D. Lentz. *Chem.-Eur. J.*, 18, 10701 (2012)
- [97] A.G. Algarra, M.G. Basallote, M.J. Fernández-Trujillo, M. Feliz, E. Guillamon, R. Llusar, I. Sorribes, C. Vicent. *Inorg. Chem.*, 49, 5935 (2010)
- [98] T.F. Beltrán, M. Feliz, R. Llusar, J.A. Mata, V.S. Safont. *Organometallics*, 30, 290 (2011)

- [99] C. Alfonso, T.F. Beltrán, M. Feliz, R. Llusar. *J. Clust. Sci.*, 26, 199 (2015)
- [100] H.A. Wittcoff, B.G. Reuben, J.S. Plotkin. *Industrial Organic Chemicals*. Wiley, Hoboken. NJ, 2004
- [101] S.A. Lawrence, in *Amines: Synthesis, Properties and Applications*. (Cambridge: The Press Syndicate of the University of Cambridge, 2012). p. 1
- [102] S. Farhadi, S. Sepahvand. *J. Mol. Catal. A: Chem.*, 318, 75 (2010)
- [103] R.V. Jagadeesh, A.-E. Surkus, H. Junge, M.-M. Pohl, J. Radnik, J. Rabeah, H. Huan, V. Schünemann, A. Brückner, M. Beller. *Science*, 342, 1073 (2013)
- [104] S. Ichikawa, M. Tada, Y. Iwasawa, T. Ikariya. *Chem. Commun.*, 924 (2005)
- [105] A. Corma, P. Serna, P. Concepcion, J.J. Calvino. *J. Am. Chem. Soc.*, 130, 8748 (2008)
- [106] L.Q. Liu, B.T. Qiao, Z.J. Chen, J. Zhang, Y.Q. Deng. *Chem. Commun.*, 653 (2009)
- [107] F. Cardenas-Lizana, S. Gomez-Quero, A. Hugon, L. Delannoy, C. Louis, M.A. Keane. *J. Catal.*, 262, 235 (2009)
- [108] R. Joshi, U. Chudasama. *Ind. Eng. Chem. Res.*, 49, 2543 (2010)
- [109] I. Sorribes, G. Wienhfer, C. Vicent, K. Junge, R. Llusar, M. Beller. *Angew. Chem., Int. Ed.*, 51, 7794 (2012)
- [110] E. Pedrajas, I. Sorribes, K. Junge, M. Beller, R. Llusar. *Chem Cat Chem*, 7, 2675 (2015)
- [111] B. Zhao, Z. Han, K. Ding. *Angew. Chem., Int. Ed.*, 52, 4744 (2013)
- [112] F. Haber. *Z. Electr.*, 4, 506 (1898)
- [113] A. Corma, P. Concepción, P. Serna. *Angew. Chem., Int. Ed.*, 46, 7266 (2007)
- [114] F.A. Cotton, P.A. Kibala, M. Matusz, C.S. McCaleb, R.B.W. Sandor. *Inorg. Chem.*, 28, 2623 (1989)
- [115] C.J. Casewit, D.E. Coons, L.L. Wright, W.K. Miller, M.R. Dubois. *Organometallics*, 5, 951 (1986)
- [116] E. Pedrajas, I. Sorribes, K. Junge, M. Beller, R. Llusar. *Green Chem.*, 19, 3764 (2017)
- [117] K. Maeda, K. Domen. *J. Phys. Chem. Lett.*, 1, 2655 (2010)
- [118] W.T. Eckenhoff, R. Eisenberg. *Dalton Trans.*, 41, 13004 (2012)
- [119] D. Merki, X. Hu. *Energy Environ. Sci.*, 4, 3878 (2011)
- [120] J. Yano, J. Kern, V.K. Yachandra, H. Nilsson, S. Koroidov, J. Messinger, in *Sustaining Life on Planet Earth: Metalloenzymes Mastering Dioxygen and Other Chewy Gases*. Book Series Metal Ions in Life Sciences. Vol. 15. (Eds P.M.H. Kroneck, M.E. Sosa Torres). (Springer, 2015). p. 13
- [121] H. Vrubel, X. Hu. *ACS Catal*, 3, 2002 (2013)
- [122] W. Zhou, Z. Yin, Y. Du, X. Huang, Z. Zeng, Z. Fan, H. Liu, J. Wang, H. Zhang. *Small*, 9, 140 (2013)
- [123] Q. Liu, Z. Pu, A.M. Asiri, A.H. Qusti, A.O. Al-Youbi, X. Sun. *J. Nanopart. Res.*, 15, 2057 (2013)
- [124] X. Zong, G. Wu, H. Yan, G. Ma, J. Shi, F. Wen, L. Wang, C. Li. *J. Phys. Chem. C*, 114, 1963 (2010)
- [125] A.B. Laursen, T. Pedersen, P. Malacrida, B. Seger, O. Hansen, P.C.K. Vesborg, I. Chorkendorff. *Phys. Chem. Chem. Phys.*, 15, 20000 (2013)
- [126] P.D. Tran, S.S. Pramana, V.S. Kale, M. Nguyen, S.Y. Chiam, S.K. Batabyal, L.H. Wong, J. Barber, J. Loo. *Chem.-Eur. J.*, 18, 13994 (2012)
- [127] Z. Zhang, P. Wang. *J. Mater. Chem.*, 22, 2456 (2012)
- [128] T.F. Jaramillo, J. Bonde, J.D. Zhang, B.L. Ooi, K. Andersson, J. Ulstrup, I. Chorkendorff. *J. Phys. Chem. C*, 112, 17492 (2008)
- [129] T.F. Jaramillo, K.P. Jorgensen, J. Bonde, J.H. Nielsen, S. Hørch, I. Chorkendorff. *Science*, 317, 100 (2007)
- [130] J.K. Nørskov, T. Bligaard, A. Logadottir, J.R. Kitchin, J.G. Chen, S. Pandelov, U. Stimming. *J. Electrochem. Soc.*, 152, J23 (2005)
- [131] A.B. Laursen, S. Kegnös, S. Dahl, I. Chorkendorff. *Energy Environ. Sci.*, 5, 5577 (2012)
- [132] Y. Hou, P.C. Vesborg, L. Bech, B. Seger, S. Dahl, I. Chorkendorff, B.L. Abrams, K. Herbst, M.E. Bjørketun, J. Rossmeisl, J.K. Nørskov, T. Pedersen, O. Hansen. *J. Photon. Energy*, 2, 026001 (2012)
- [133] S.W. Seo, S. Park, H.Y. Jeong, S.H. Kim, U. Sim, C.W. Lee, K.T. Nam, K.S. Hong. *Chem. Commun.*, 48, 10452 (2012)
- [134] J. Kibsgaard, T.F. Jaramillo, F. Besenbacher. *Nat. Chem.*, 6, 248 (2014)
- [135] H.I. Karunadasa, E. Montalvo, Y. Sun, M. Majda, J.R. Long, C.J. Chang. *Science*, 335, 698 (2012)
- [136] L. Ye, L. Zan, L. Tian, T. Peng, J. Zhang. *Chem. Commun.*, 47, 6951 (2011)
- [137] J. Xiong, G. Cheng, F. Qin, R. Wang, H. Sun, R. Chen. *Chem. Eng. J.*, 220, 228 (2013)
- [138] J. Xia, J. Di, S. Yin, H. Xu, J. Zhang, Y. Xu, L. Xu, H. Li, M. Ji. *RSC Adv.*, 4, 82 (2014)
- [139] Y. Fang, Y. Huang, J. Yang, P. Wang, G. Cheng. *Environ. Sci. Technol.*, 45, 1593 (2011)
- [140] D. Yue, T. Zhang, M. Kan, X. Qian, Y. Zhao. *Appl. Catal. B*, 183, 1 (2016)
- [141] A.P.V. Soares, M.F. Portela, A. Kiennemann. *Catal. Rev.*, 47, 125 (2005)

- [142] Y. Ono. *Catal. Today*, 81, 3 (2003)
- [143] T. Waters, R.A.J. O'Hair, A.G. Wedd. *J. Am. Chem. Soc.*, 125, 3384 (2003)
- [144] Y.K. Kim, R. Rousseau, B.D. Kay, J.M. White, Z. Dohnalek. *J. Am. Chem. Soc.*, 130, 5059 (2008)
- [145] C. Vicent, M. Feliz, R. Llusar. *J. Phys. Chem. A*, 112, 12550 (2008)
- [146] T.F. Beltran, M. Feliz, R. Llusar, V.S. Safont, C. Vicent. *Catal. Today*, 177, 72 (2011)
- [147] T. Tatsumi, M. Taniguchi, H. Ishige, Y. Ishii, T. Murata, M. Hidai. *Appl. Surf. Sci.*, 121, 500 (1997)
- [148] M. Taniguchi, D. Imamura, H. Ishige, I. Youichi, T. Murata, M. Hidai, T. Tatsumi. *J. Catal.*, 187, 139 (1999)
- [149] W. Bensch, in *Comprehensive Inorganic Chemistry II. Superface Inorganic Chemistry Heterogeneous Catalysis*. (2nd Edn). Vol. 7. (Elsevier, 2013). p. 287
- [150] R.R. Chianelli, G. Berhault, P. Raybaud, S. Kasztelan, J. Hafner, H. Toulhoat. *Appl. Catal., A*, 227, 83 (2002)
- [151] L.I. Merino, A. Centeno, S.A. Giraldo. *Appl. Catal., A*, 197, 61 (2000)
- [152] M.D. Curtis. *Appl. Organomet. Chem.*, 6, 429 (1992)
- [153] K. Herbst, M. Monari, M. Brorson. *Inorg. Chem.*, 41, 1336 (2002)
- [154] A. Puig-Molina, L.P. Nielsen, A.M. Molenbroek, K. Herbst. *Catal. Lett.*, 92, 29 (2004)
- [155] K. Herbst, M. Monari, M. Brorson. *Inorg. Chem.*, 40, 2979 (2001)
- [156] M. Feliz, R. Llusar, S. Uriel, C. Vicent, M. Brorson, K. Herbst. *Polyhedron*, 24, 1212 (2005)
- [157] K. Herbst, M. Brorson, A. Carlsson. *J. Mol. Catal. A: Chem.*, 325, 1 (2010)
- [158] E.M. Guillaumon, M. Blasco, R. Llusar. *Inorg. Chim. Acta*, 424, 248 (2015)
- [159] E.C. Constable. *Chem. Soc. Rev.*, 42, 1637 (2013)
- [160] R. Frantz, E. Guillaumon, J. Lacour, R. Llusar, V. Polo, C. Vicent. *Inorg. Chem.*, 46, 10717 (2007)
- [161] T. Portada, M. Roje, Z. Raza, V. Čaplar, M. Žinić, V. Šunjić. *Eur. J. Org. Chem.*, 5, 838 (2007)
- [162] M. Feliz, E. Guillaumon, R. Llusar, C. Vicent, S.E. Stiriba, J. Perez-Prieto, M. Barberis. *Chem.-Eur. J.*, 12, 1486 (2006)
- [163] R. Faust. *Angew. Chem., Int. Ed*, 40, 2251 (2001)
- [164] H. Pellissier. *Tetrahedron*, 64, 7041 (2008)
- [165] J. Long, H. Du, K. Li, Y. Shi. *Tetrahedron Lett.*, 46, 2737 (2005)
- [166] É. Lévesque, S.R. Goudreau, A.B. Charette. *Org. Lett.*, 16, 1490 (2014)
- [167] M. Ciampini, P. Perlmutter, K. Watson. *Tetrahedron: Asymmetry*, 18, 243 (2007)
- [168] E. Guillaumon, R. Llusar, J. Perez-Prieto, S.E. Stiriba. *J. Organomet. Chem.*, 693, 1723 (2008)
- [169] A.I. Carrillo, J. Garcia-Martinez, R. Llusar, E. Serrano, I. Sorribes, C. Vicent, J.A. Vidal-Moya. *Microporous Mesoporous Mater.*, 151, 380 (2012)
- [170] R.A. Sheldon. *Chem. Soc. Rev.*, 41, 1437 (2012)
- [171] G. Blay, J.R. Pedro, C. Vila, in *Catalytic Asymmetric Friedel - Crafts Alkylations*. (Eds M. Bandini, A. Umani-Rohcni). (Weinheim: Wiley-VCH, 2009). p. 223
- [172] A.B. Zaitsev, S. Gruber, P.A. Pluss, P.S. Pregosin, L.F. Veiros, M. Worle. *J. Am. Chem. Soc.*, 130, 11604 (2008)
- [173] I. Usui, S. Schmidt, M. Keiler, B. Breit. *Org. Lett.*, 10, 1207 (2008)
- [174] I. Takei, K. Suzuki, Y. Enta, K. Dohki, T. Suzuki, Y. Mizobe, M. Hidai. *Organometallics*, 22, 1790 (2003)
- [175] Y. Tao, Y. Zhou, J. Qu, M. Hidai. *Tetrahedron Lett.*, 51, 1982 (2010)
- [176] I. Takei, K. Kobayashi, K. Dohki, M. Hidai. *Inorg. Chem.*, 46, 1045 (2007)
- [177] M. Kimura, M. Fukasaka, Y. Tamaru. *Heterocycles*, 67, 535 (2006)
- [178] Y. Tao, Bo Wang, Baomin Wang, L. Qu, J. Qu. *Org. Lett.*, 12, 2726 (2010)
- [179] Y. Tao, B. Wang, J. Zhao, Y. Song, L. Qu, J. Qu. *J. Org. Chem.*, 11, 2942 (2012)
- [180] T. Murata, Y. Mizobe, H. Gao, Y. Ishii, T. Wakabayashi, F. Nakano, T. Tanase, S. Yano, M. Hidai, I. Echizen, H. Nanikawa, S. Motomura. *J. Am. Chem. Soc.*, 116, 3389 (1994)
- [181] T. Wakabayashi, Y. Ishii, T. Murata, Y. Mizobe, M. Hidai. *Tetrahedron Lett.*, 36, 5585 (1995)
- [182] T. Wakabayashi, Y. Ishii, K. Ishikawa, M. Hidai. *Angew. Chem., Int. Ed. Engl.*, 35, 2123 (1996)
- [183] M. Hidai, S. Kuwata, Y. Mizobe. *Acc. Chem. Res.*, 33, 46 (2000)
- [184] L. Takei, K. Dohki, K. Kobayashi, T. Suzuki, M. Hidai. *Inorg. Chem.*, 44, 3768 (2005)
- [185] B.K. Burgess, D.J. Lowe. *Chem. Rev.*, 96, 2983 (1996)
- [186] P.C. Dos Santos, R.Y. Igarashi, H.I. Lee, B.M. Hoffman, L.C. Seefeldt, D.R. Dean. *Acc Chem. Res.*, 38, 208 (2005)
- [187] T. Spatzal, J. Schlesier, E.-M. Burger, D. Sippel, L. Zhang, S.L.A. Andrade, D.C. Rees, O. Einsle. *Nat. Commun.*, 1, 10902 (2016)

- [188] T.E. Wolff, J.M. Berg, C. Warrick, K.O. Hodgson, R.H. Holm, R.B. Frankel. *J. Am. Chem. Soc.*, 100, 4630 (1978)
- [189] Y. Zhang, J.L. Zuo, H.C. Zhou, R.H. Holm. *J. Am. Chem. Soc.*, 124, 14292 (2002)
- [190] S. Ohta, Y. Ohki, T. Hashimoto, R.E. Cramer, K. Tatsumi. *Inorg. Chem.*, 51, 11217 (2012)
- [191] P.K. Mascharak, W.H. Armstrong, Y. Mizobe, R.H. Holm. *J. Am. Chem. Soc.*, 105, 475 (1983)
- [192] D. Coucouvanis, K.D. Demadis, C.G. Kim, R.W. Dunham, J.W. Kampf. *J. Am. Chem. Soc.*, 115, 3344 (1993)
- [193] D.V. Fomitchev, C.C. McLauchlan, R.H. Holm. *Inorg. Chem.*, 41, 958 (2002)
- [194] K. Arashiba, Y. Miyake, Y. Nishibayashi. *Nat. Chem.*, 3, 120 (2011)
- [195] S. Kuriyama, K. Arashiba, K. Nakajima, H. Tanaka, N. Kamaru, K. Yoshizawa, Y. Nishibayashi. *J. Am. Chem. Soc.*, 136, 9719 (2014)
- [196] S. Takemoto, J. Ohata, K. Umetani, M. Yamaguchi, H. Matsuzaka. *J. Am. Chem. Soc.*, 136, 15889 (2014)
- [197] E.S. Borren, A.F. Hill, R. Shang, M. Sharma, A.C. Willis. *J. Am. Chem. Soc.*, 135, 4942 (2013)
- [198] R.D. Young, A.F. Hill, G.E. Cavigliasso, R. Stranger. *Angew. Chem., Int. Ed.*, 52, 3699 (2013)
- [199] Yu.V. Mironov, Yu.M. Gayfulin, S.G. Kozlova, A.I. Smolentsev, M.S. Tarasenko, A.S. Nizovtsev, V.E. Fedorov. *Inorg. Chem.*, 51, 4359 (2012)
- [200] X.D. Chen, W. Zhang, J.S. Duncan, S.C. Lee. *Inorg. Chem.*, 51, 12891 (2012)
- [201] A. Hejl, T.M. Trnka, M.W. Day, R.H. Grubbs. *Chem. Commun.*, 2524 (2002)
- [202] A. Reinholdt, K. Herbst, J. Bendix. *Chem. Commun.*, 52, 2015 (2016)